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Final Report

UV and Optical Covariability of O Star Winds

Joy S. Nichols

A worldwide, multiwavelength observing campaign of the O7.5III(n)((f)) star ξ Per was performed in 1991 with nearly continuous optical and ultraviolet coverage during several days. The results of this campaign present strong evidence that stellar-wind variability, as observed in the variable discrete components in UV resonance lines, originates in the same region where Hα is formed, which is presumably close to the star.

The most noticeable variable stellar wind features are the Discrete Absorption Components (DACs) in the resonance doublet of Si IV (see Fig. 1a). DACs are found in winds of essentially all early-type stars. They appear at low (negative) velocity and accelerate asymptotically through the profile towards high velocity. The quasi-periodic behavior of their delvelopment is likely due to the rotation of the star, but how the stellar wind is tied to the surface is not known. Why these DACs develop in the first place is also still unestablished, and the goal of this research was focused on finding how close to the star these features can be traced.

In ξ Per it was found that the DACs in Si IV (Fig. 1a) begin at the same time as the enhanced-absorption phases between -200 and -500 km s^{-1} in the subordinate N IV P Cygni line (Fig. 1b). This low-velocity region must be located near the star, implying that the DACs develop from a region where the radial outflow reaches 200 km s^{-1}, which is comparable to the rotation velocity of the star.

Simultaneous with the study period of IUE, Hα spectra were obtained from the Haute Provence Observatory with the Aurélie spectrograph attached to the 1.5m telescope. The Hα profiles also clearly show variability (Fig. 1c). The equivalent width varies in concert with the DACs (Fig. 1d). Just before a new DAC in the UV starts, the Hα profile develops excess emission in the line core, followed by enhanced absorption at negative velocities. This is the strongest evidence ever found that DACs can be traced back to very near the photosphere. Similar correlations between UV and Hα variability for other O stars has been found as well.

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WIND-VARIABILITY OF O-TYPE STARS

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ABSTRACT We report on our ongoing observational research on stellar-wind variability in early-type stars. This fundamental property of winds is most prominently observed in the blue-shifted absorption parts of P Cygni-type profiles in the ultraviolet region. In unsaturated profiles Discrete Absorption Components (DACs) migrate, after their sudden appearance, from intermediate velocities towards the terminal velocity, v_∞, of the radiatively-driven wind. In saturated profiles, variability is found in the blue edge at velocities exceeding v_∞. Through simultaneous optical observations we investigate whether the wind variability is triggered from the stellar photosphere.

INTRODUCTION

O stars lose a significant fraction of their initial mass during the evolution through a stellar wind. About one solar mass in $10^5 - 10^6$ years flows back into the interstellar medium, reaching velocities up to 1% of the speed of light, which makes O stars the most important mass and energy donors of the ISM. The presence of stellar winds are primarily recognized from the P Cygni-type profiles of ultraviolet resonance lines of C IV, Si IV and N V. A supersonically expanding atmosphere is indicated by the blue-shifted absorption trough, formed in regions in front of the stellar disk, and the emission peak. Also radio and infrared measurements of free-free radiation, emission lines (e.g. Hα, HeII 4686Å) in optical spectra, X-rays formed by accretion on a compact object in massive X-ray binaries, and stellar-wind bubbles betray the existence of strong winds around O-type stars.
The mass-loss rate $\dot{M}$ scales roughly with the luminosity as $L^{1.6}$ and the terminal velocity of the wind, v_∞, is roughly proportional to the escape velocity at the stellar surface (Abbott, 1982). This can be rather well explained by radiation-

velocities in the subordinate N IV line, which is most probably formed close to the star, simultaneous with the DACs in the Si IV P Cygni profile (see Fig. 3, Henrichs *et al.*, 1992). The picture emerges that the different kinds of variability we observe actually represent the same phenomenon, but that it depends on the saturation level of the profiles which aspect is most pronounced. The question why and where DACs start to develop is, however, unknown.

ORIGIN OF STELLAR-WIND VARIABILITY

Does the observed variability represent an intrinsic property of a radiatively-driven wind or is this variability in the wind triggered by changes taking place at or close to the photosphere of the star? In a series of papers, Owocki and collaborators showed that the unstable character of the acceleration mechanism of radiatively-driven winds can result in a highly structured stellar wind (e.g. Owocki *et al.*, 1988, Owocki, 1991). Time-dependent 1-D hydrodynamical calculations revealed that small perturbations grow exponentially into shocks. The effect of scattering in the models is that the exponential growth of perturbations in the base of the wind is dragged, resulting in a shocked wind structure only there where the mean velocity of the wind exceeds $\approx 0.5\ v_\infty$. If DACs are interpreted in this model to be caused by clumped material, present in and moving through the stratified wind, it naturally explains why DACs are mostly found at velocities $\geq 0.5\ v_\infty$. The highest velocities occuring in the low-density parts of the shocks easily exceed the v_∞, reached by the DACs. This could be the cause for the "extra" broadening of the saturated P Cygni absorption troughs. A big problem, which is not (yet?) solved by these models, is the slow acceleration of DACs. As can be seen in Fig. 1, the acceleration of a DAC can take more than 5 days, which is much slower than the predicted acceleration of the clumped wind regions, which is about one day. The observed low velocity N IV variability (Fig. 3) suggests that DACs originate from regions close to the stellar photosphere, and one should be able to find other variable spectral lines formed in these regions. Therefore, we organized multiwavelength observing campaigns to study the variability in optical lines like Hα and HeII 4686Å and UV P Cygni profiles simultaneously. We found that most of our target stars showed variability both in near-photospheric and in wind regions. Figure 4a shows changes in the Hα profile of α Cam (O9.5Ia) during two nights of observation. We did not, however, find any variability in the UV P Cygni profiles for this star, probably because these profiles were too saturated. A positive example of simultaneous changes observed in line profiles formed in different regions of the wind was found in λ Cep (O6.5I(n)fp). In Fig. 1b we present the changes in the steep blue edge of the C IV P Cygni profile. In simultaneous observations of the HeII 4686Å line, collected at Kitt Peak (U.S.A.) and Calar Alto (Spain), we detected strong variability (Henrichs, 1991). We computed the equivalent width of both the C IV absorption and the HeII 4686Å line and plotted these quantities as a function of time (Fig. 4b). Striking is the fact that both lines show the same variation in their equivalent width, especially when one realizes that the HeII 4686Å line

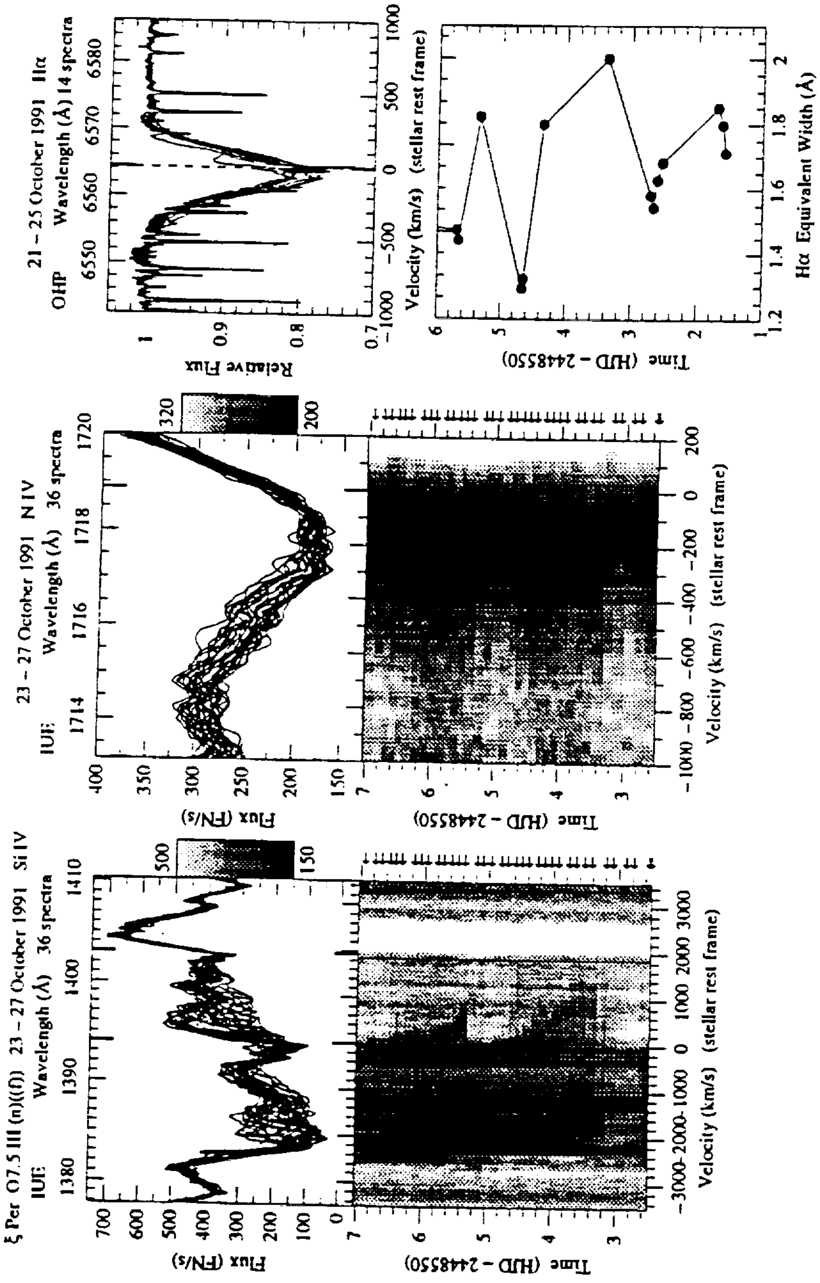

Fig. 1. Hα spectra of ξ Per. The upper panel shows an overplot of the data, with superposed an adopted photospheric profile by which the spectra are divided to obtain the quotient spectra in the middle panel. This brings out the relative behavior. The timesequence is shown in the lower panel in the form of grayscale plots. Note the enhanced emission at −50 km/s, changing into absorption at −200 km/s, just prior to the development of the DACs in Fig. 1.

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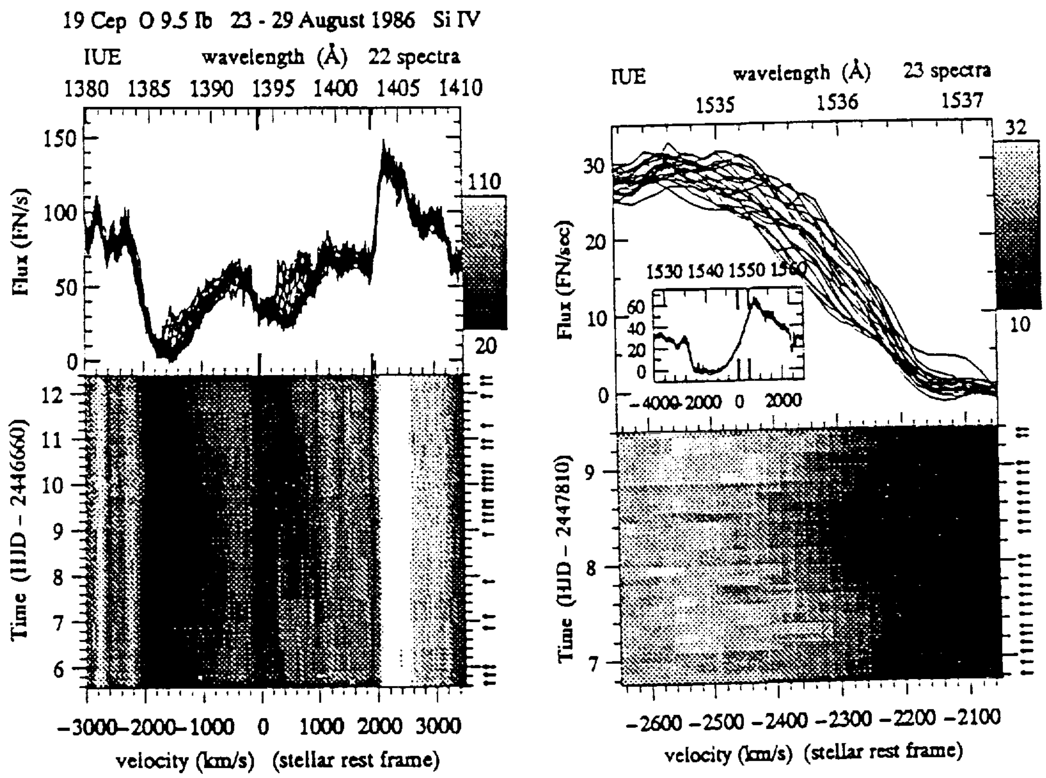

Figure 1: a) DAC behaviour in the Si IV resonance doublet of 19 Cep O9.5Ib. An arrow indicates the mid-exposure time of each spectrum; the intensity is converted into a gray-scale; b) Variability in the steep blue edge of the C IV profile of λ Cep O6I(n)fp.

driven wind theory, initiated by Lucy & Solomon (1970) and further developed by Castor, Abbott & Klein(CAK) (1975). By scattering photons from the radiation field into millions of lines, and thus absorbing momentum, the upper layers of the atmosphere are accelerated towards velocities exceeding 100 Mach. Recent refinements of the CAK theory by Friend & Abbott (1986) and Pauldrach, Puls & Kudritzki (1986) resulted in a self-consistent theory describing radiatively-driven winds. Nowadays, a comparison between calculated and observed wind profiles can reveal fundamental parameters like mass, radius and luminosity of the star (see e.g. Kudritzki & Hummer, 1990). Because of the fact that properties like luminosity and gravity, which are constant in time, determine the dynamics of a stellar wind, we do not, at first, expect variability.

VARIABILITY OF UV P CYGNI PROFILES

As shown in Fig. 1, the Si IV resonance doublet near 1400 Å of 19 Cep, an O9.5Ib supergiant, exhibits variability in the wind on a daily timescale. From such time-dependent studies it became clear that these variations are not chaotic, but occur in a well-defined pattern (e.g. Prinja *et al.*, 1987, Henrichs *et al.*, 1988): broad

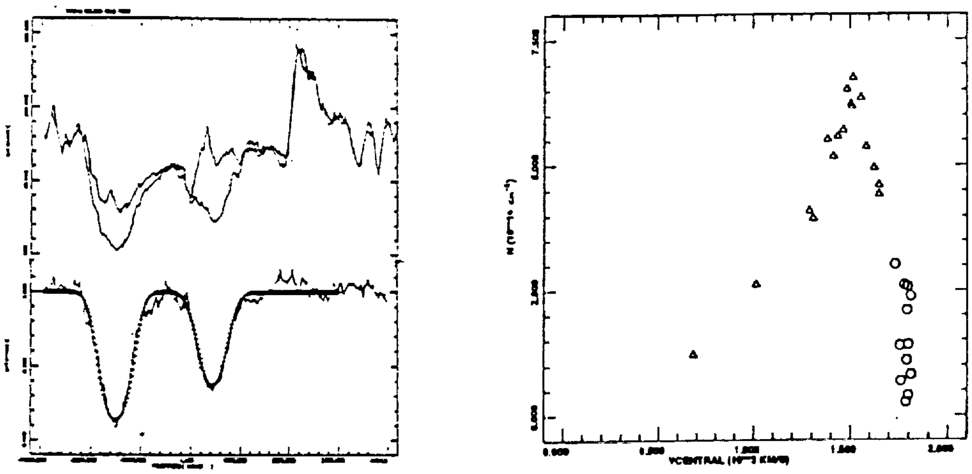

Figure 2: a) Si IV P Cygni profile of 19 Cep O9.5Ib (#22 in Fig. 1) plotted on top of the template spectrum. The quotient spectrum (bottom) shows the isolated DAC and a gaussian fit (plus symbols); b) Column density of a DAC as a function of central velocity (i.e. time) for 19 Cep O9.5Ib.

absorption enhancements appear episodically at low, but supersonic, velocity and accelerate through the profile until a final velocity (i.e. 0.8-0.9 v_{edge}, the velocity corresponding to the bottom of the steep blue edge of saturated P Cygni lines) is reached. During the acceleration phase, which takes place on the order of days (depending on the star), the width of the absorptions decreases. Because of their characteristic appearance these features are called "discrete absorption components" (DACs). DACs have been found in UV spectra of more than 80% of 203 O-type stars (Howarth & Prinja, 1989).
To study the detailed DAC behaviour, we divided each profile by a constructed template spectrum, which is aimed to contain a minimum amount of absorption. This can be done because the profile often returns to the same minimum after a DAC passage. In Fig. 2a a Si IV profile of the O9.5Ib star 19 Cep is shown together with the template spectrum and the quotient spectrum. To model the DACs, we fit the quotient spectra, taking into account both doublet components simultaneously, including the known oscillator strength ratio and doublet separation. By modeling the DACs in this way, we could study the evolution of central velocity, width and the derived column density of the DACs. We find for all stars that the column density reaches a maximum at a central velocity of about 1500 km/s (Fig. 2b). A simple way of modeling this change in column density is in terms of spherical expansion of an opaque blob moving through the wind and becoming optically thin before the stellar disk is totally covered. In such a model the expansion radius can be mapped against time, giving an average velocity law for a DAC. This poses constraints on a physical model. Other sophistications, like rotation and density inhomogeneities could be build in, but are probably too ad hoc in the present stage of analysis.
It has been suggested that the final velocity reached by a DAC (0.8-0.9 v_{edge})

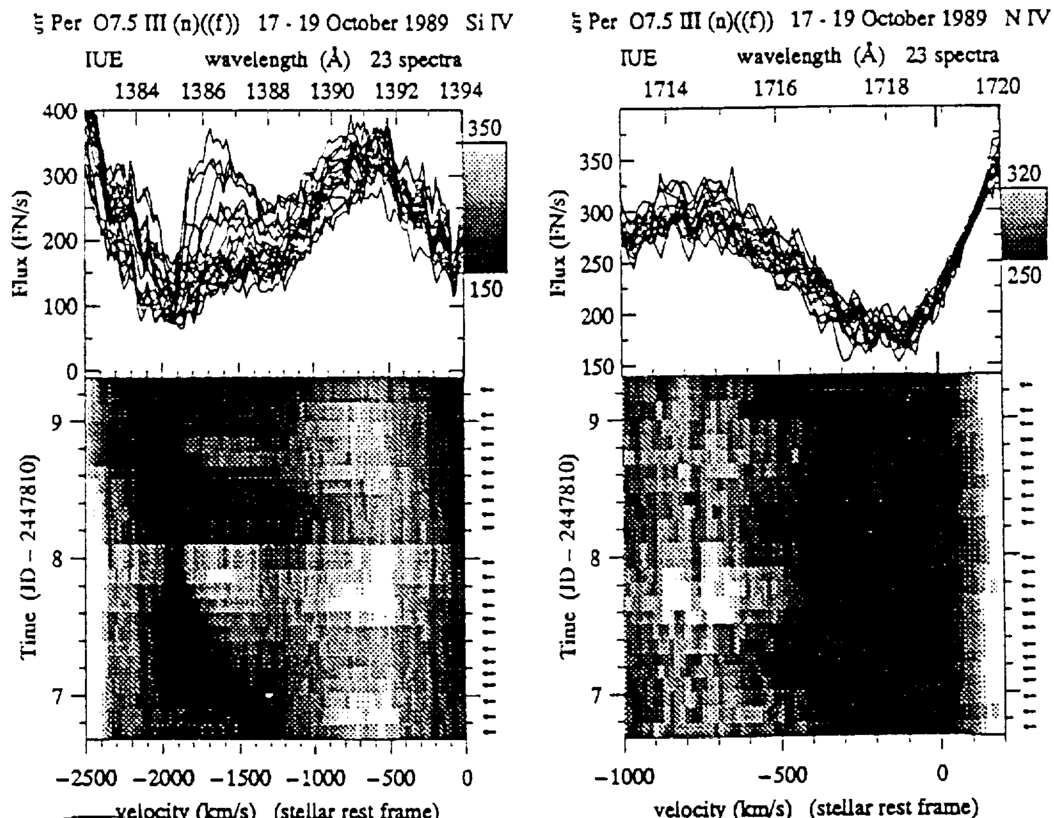

Figure 3: a) DACs in the Si IV resonance doublet of ξ Per O7.5III(n)((f)); b) Simultaneous changes, but at much smaller velocities, in the subordinate N IV line at 1718Å.

in fact represents the "true" terminal velocity, i.e. v_∞, of the wind (Henrichs *et al.*, 1988). The extra broadening beyond the steep blue edge of saturated P Cygni profiles can be caused by "turbulence" in the wind (Groenewegen & Lamers, 1989). Furthermore, the recurrence timescale of DACs scales, for the few stars observed, roughly proportional to $v_{\rm rot} \sin i$ (Prinja, 1988, and Henrichs *et al.*, 1988). For example, the left panels of Figs. 1 and 3 show that the DAC event in 19 Cep is much "slower" than in ξ Per, corresponding to $v_{\rm rot} \sin i = 40$ km/s and 200 km/s, respectively. A long-term study of stellar-wind variability (Kaper *et al.*, 1990) revealed that the detailed DAC "pattern" differs from star to star, but each star shows the same characteristics (and thus timescales) every year it is observed. This suggests that rotation must play an important role.

DACs in unsaturated P Cygni profiles are the most pronounced indicators of stellar-wind variability. But also saturated P Cygni profiles (like C IV of λ Cep in Fig. 1) exhibit large variations. We found up to 15% changes in $v_{\rm edge}$ of these profiles, which in the interpretation above means a variable turbulence in the wind. We did not find an obvious correlation, valid for all stars and for all datasets, between DAC behaviour in unsaturated lines and changes in $v_{\rm edge}$ in saturated lines. For the star ξ Per we also found changes at much smaller

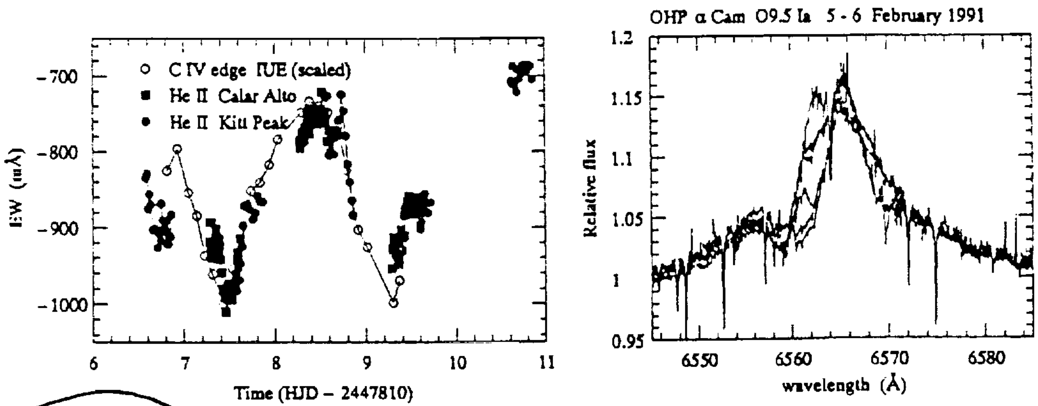

Figure 4: a) The correspondence between changes in equivalent width of the HeII 4686Å line (filled symbols) and the C IV P Cygni absorption (open symbols) of λ Cep (O6.5I(n)fp); b) Two nights of observations at O.H.P. (France) of the Hα profile of α Cam (O9.5Ia). Note the dramatic changes in emission strength.

must be formed very close to the star, where apparently the highest velocities ($\geq$ 2300 km/s) in the wind are also present. Further interpretation of our recent observing campaigns held in February and October 1991 is still underway. With these observations we should be able to detect a connection between near-photospheric and wind variability, if such a connection exists at all.

REFERENCES

Abbott, D.C. 1982, *Ap. J.* **259**, 282

Castor, J.I., Abbott, D.C., Klein, R.K. 1975, *Ap. J.* **195**, 157

Friend, D., Abbott, D.C. 1986, *Ap. J.* **311**, 701

Groenewegen, M.A.T., Lamers, H.J.G.L.M. 1989, *Astron. Astr.* **221**, 78

Henrichs, H.F., 1991, in *Proc. ESO Workshop on rapid variability in OB stars*, Ed. D. Baade

Henrichs, H.F., Kaper, L., Nichols-Bohlin, J. 1992, *Astr. Ap.*, in press

Henrichs, H.F., Kaper, L., Zwarthoed, G.A.A. 1988, in *Proc. Decade of UV astronomy with IUE*, ESA SP-281

Howarth, I.D., Prinja, R.K. 1989, *Ap. J. Supp. Ser.* **69**, 527

Kaper, L., Henrichs, H.F., Zwarthoed, G.A.A., Nichols-Bohlin, J. 1990, in *Proc. Angular momentum and mass loss for hot stars*, Eds. Willson and Stalio, NATO SI C316, p. 213

Kudritzki, R.P., Hummer, D.A. 1990, *Annu. Rev. Astron. Astroph.* **28**, 303

Lucy, L.B., Solomon, P.M. 1970, *Ap. J.* **159**, 879

Owocki, S.P. 1991, in *Stellar Atmospheres: Beyond Classical Models*, Eds. Crivellari, Hubeny, and Hummer, NATO SI 341, p. 235

Owocki, S.P., Castor, J.I., Rybicki, G.B. 1988, *Ap. J.* **335**, 914

Pauldrach, A., Puls, J., Kudritzki, R.P. 1986, *Astr. Ap.* **164**, 86

Prinja, R.K. 1988, *M.N.R.A.S.* **231**, 21P

Prinja, R.K., Howarth, I.D., Henrichs, H.F. 1987, *Ap. J.* **317**, 389

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